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Water storage variations in the Poyang Lake Basin estimated from GRACE and satellite altimetry

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ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) satellite mission provides a unique opportunity to quantitatively study terrestrial water storage (TWS) variations. In this paper, the terrestrial water storage variations in the Poyang Lake Basin are recovered from the GRACE gravity data from January 2003 to March 2014 and compared with the Global Land Data Assimilation System (GLDAS) hydrological models and satellite altimetry. Furthermore, the impact of soil moisture content from GLDAS and rainfall from the Tropical Rainfall Measuring Mission (TRMM) on TWS variations are investigated. Our results indicate that the TWS variations from GRACE, GLDAS and satellite altimetry have a general consistency. The TWS trends in the Poyang Lake Basin determined from GRACE, GLDAS and satellite altimetry are increasing at 0.0141 km^3/a, 0.0328 km^3/a and 0.0238 km^3/a, respectively during the investigated time period. The TWS is governed mainly by the soil moisture content and dominated primarily by the precipitation but also modulated by the flood season of the Yangtze River as well as the lake and river exchange water.

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1. Introduction

Terrestrial water cycle has, among others, important influence on the climate change, ecological environment and human social progress. The terrestrial water storage (TWS) variations comprise the variations of rainfall, evaporation, surface runoff, soil water, groundwater, and other effects. The investigation of TWS changes provides an important basis for studying and predicting the weather and climate change, exploring the global and local water cycle, management of agricultural production, prevention and control of flood and water management [1]. However, the detailed TWS variations are difficultly quantified due to limited in situ observations such as groundwater, precipitation, snow water equivalent, soil moisture, evapotranspiration, and others at small basins

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or smaller scales areas [2]. Imaging satellite techniques and satellite altimetry can only monitor the surface water, but normally represent just one component of TWS, while empirical models are useful but exhibit limited accuracy. Moreover, the in situ measurements tend to be point measurements, while the remote sensing measurements can only detect the near surface TWS variations [3].

The Gravity Recovery and Climate Experiment (GRACE) satellite mission, launched in March 2002, provides a unique opportunity to quantitatively investigate the TWS variations at regional and global scales. In recent years, the GRACE data have been widely used to estimate the global or regional water storage variations and the groundwater variations [4,5]. Hassan and Jin [6], for instance, investigated the total water discharge in the Great Rift Valley of East Africa (i.e. Lakes Victoria, Tanganyika, and Malawi) by using the GRACE data between January 2003 and December 2012 and found a significant decrease in the lake levels over the period from 2003 to 2006. The TWS variations from GRACE showed a good consistency with the lake level variations from the satellite altimetry. They also found that Tropical Rainfall Measuring Mission (TRMM) rainfall preceded the GRACE TWS variations by 2 months. Yang and Chen [7] recovered the TWS variations in the Tianshan Mountains and surrounding areas from the GRACE temporal gravity coefficients over the period from January 2003 to March 2013. The water storage variations exhibited typical seasonal changes, with the monthly maximum occurring in April and the corresponding monthly minimum in October. They also demonstrated that the TWS variations from the GRACE data have a good consistency with the results from Global Land Data Assimilation System (GLDAS). GRACE monthly gravity data from January 2003 to December 2010 were used to infer the TWS variations in the Qilian Mountains [8]. Results showed that the TWS variations were different on the spatial distribution, lower in the east and the north, while higher in the west and the south. The TWS showed an increasing trend during the investigated period, with an average rate of 0.72 mm per month and increased to about 13.6×10^8 m^3 totally during the 8 years. The TWS variations in the Heihe River Basin estimated from GRACE between April 2004 and June 2011 indicated a decreasing trend at the rate of 2.3 cm/a in terms of equivalent water height (EWH) and showed a good agreement with the regional climate changes and the global hydrological model provided by the Climate Prediction Center (CPC) [9]. The groundwater storage variations exhibited a decreasing trend at the rate of 2.5 cm/a in EWH. The estimated decreasing rates were almost the same in the upstream and midstream areas, but larger than the rate of downstream area of the Heihe River Basin. Pereira et al. [10] used the GRACE data to study the annual and seasonal water storage variations in the La Plata Basin during the period between 2002 and 2009 and found a significant decrease of TWS during 2009 with the minimum value (−240 mm/a in EWH) during Autumn. Long et al. [11] detected a significant depletion in TWS of 62.3 ± 17.7 km^3 during 2011 in Texas from GRACE satellite observations, which agreed well with the most extreme drought in 2011 in this region. Frappart et al. [12] estimated the TWS variations in the Amazon Basin from GRACE data between 2003 and 2010 and detected some recent extreme climatic events in Amazon Basin, which included droughts during 2005 and 2010 and flooding in 2009. Wang et al. [13] estimated the reservoir volume changes from GRACE in the Three Gorges Reservoir (TGR) and compared these estimates with the in situ measurements from April 2002 to May 2010, which agreed well with the in situ measurements and the estimation of impounded water volume. These results indicated that GRACE can well estimate water storage variations at regional and global scales.

The river–lake water exchange of the Poyang Lake Basin was investigated by Caiet al. [14] using the TRMM and GRACE data, showing a significant decreasing trend of the runoff during 2003, corresponding to an increased water volume of 6.02 km^3. The GRACE satellites can improve our understanding of the water circulation and provide a basis for better predicting of the global climate change, land surface evaporation, drought and researching the water resources change process. Therefore, the TWS variations in lakes and reservoirs can also be detected by the GRACE observations [15]. However, water storage variations in the Poyang Lake Basin are still not clear due to the lack of measurements. In this paper, the TWS variations in the Poyang Lake Basin are jointly investigated by the long GRACE data (from January 2003 to March 2014), satellite altimetry, global hydrological model GLDAS and the Tropical Rainfall Measuring Mission (TRMM). Furthermore, some impacts on TWS are also studied in order to better understand the TWS variations in the Poyang Lake Basin as well as the downstream Yangtze River.

2. Data and methods

2.1. Studied area

The Poyang Lake Basin is located in approximately 28°–30°N, and 115°–117°E (see Fig. 1). It is divided into two parts by the Songmen Mountain. The northern part is the water channel connecting to the Yangtze River. The southern part is the main lake. The Poyang Lake is 173 km long from north to south. The lakeshore length is about 1200 km and the area of the water body is 3283 km^2. The water volume is about 27.6×10^9 m^3. It is the largest fresh lake in China, which holds water from five rivers, namely Ganjiang River, Fuhe River, Xinjiang River, Raohe River and Xiushui River with the water discharge into the Yangtze River. The seasonal water body fluctuations are large. The lake area can reach up to 3000 km^2 during the wet season while shrink to less than 1000 km^2 during the dry season [16]. The area of the watershed is 162.2×10^3 km^2, accounting for about 9% of the Yangtze River Basin and even nearly 96.85% of the land area of Jiangxi Province. The annual mean runoff of the watershed is 152.5×10^9 m^3, taking up to 16.3% of the watershed in the Yangtze River. The Poyang Lake plays an important role in flood diversion and storage while maintaining regional and national ecological security.

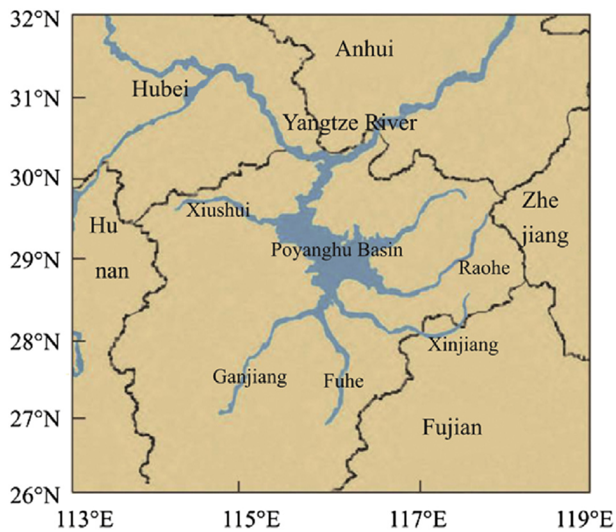

Fig. 1 – Geographical location of the Poyang Lake Basin.

2.2. *Terrestrial water storage from GRACE*

The GRACE satellites can accurately monitor the change of the Earth's gravitational field reflecting directly the mass redistribution within the Earth. The latest Release-05 (RL05) L2 solutions provided by University of Texas at Austin – Center for Space Research (CSR) German Research Centre for Geosciences (GFZ), and Jet Propulsion Laboratory (JPL) are used. The data from GFZ and JPL were truncated to degree and order of 60 to be compatible with CSR data. The spatial resolution, accuracy and periodical characteristics of the latest release of RL05 data are all better than RL04 solutions [17]. The second zonal coefficient C_{20} in RL05 data is replaced from the satellite laser ranging (SLR) observations since GRACE is not sensitive to C_{20} [18]. We further subtracted the mean gravity value of 126 months from monthly gravity values. The model is already corrected for the influence of the lunar-solar gravitational effect, atmospheric tide, pole tide, Earth tide and ocean tide and other effects. The terrestrial mass variations recovered from GRACE thus comprise mainly the hydrological signal, i.e. the TWS variations [19]. The TWS variations are defined in the spectral domain in the following form [5]:

$$\Delta\eta(\theta,\phi) = \frac{a\rho_{\mathrm{ave}}}{3\rho_{\mathrm{W}}}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\overline{P_{lm}}(\cos\theta)\frac{2l+1}{1+k_l}(\Delta C_{lm}\cos(m\phi) + \Delta S_{lm}\sin(m\phi)) \tag{1}$$

where a is the equatorial radius of the Earth; θ and ϕ are spherical co-latitude and longitude, respectively; $P_{lm}(cos\theta)$ are the (fully-normalized) associated Legendre functions; ρ_{ave} is the average density of the Earth (=5517 kg/m^3); ΔC_{lm} and ΔS_{lm} are variations of the spherical harmonic coefficients; k_l is the load Love number of degree l; ρ_W is the density of water; and $\Delta\eta(\theta,\varphi)$ is the change in surface mass expressed in the equivalent water height.

Swenson and Wahr [20] examined the spectral signature of the correlated errors in the gravity field coefficients, and suggested method of suppressing the noise from the GRACE satellite observations. They applied the correlated-error filter based on the filter width of $w = 5$ for spherical harmonics of orders above degree 7. In addition, as the model coefficient errors increase rapidly with the increasing order l, and the contribution of high-order terms cannot be ignored, the Gaussian smoothing function with 500 km half width is also adopted to reduce the estimation errors of the TWS variations from GRACE.

2.3. *Satellite altimetry*

Since 1993, the satellite altimetry data have been used to monitor the water level variations of many large inland water bodies including wetland zones, reservoirs, lakes and river channels. The U.S. Department of Agriculture's Foreign Agricultural Service (USDA-FAS) in co-operation with the National Aeronautics and Space Administration and the University of Maryland has been monitoring the water height variations of 75 major lakes worldwide. The results, provided by the U.S. Department of Agriculture's Foreign Agricultural, are publically available at: http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir. The main objective of this project was to provide time-series of water height variations for some world's largest lakes and reservoirs whose areas exceed 100 km^2 and are located within important agricultural regions. The time series of water level variations in the largest lakes (such as the Laurentian Great Lakes, Lakes Victoria and Tanganyika in Africa) are expected to have the accuracy better than 10 cm in terms of the root-mean-square (RMS). Smaller lakes (such as Lake Chad) or those that experience more sheltered conditions are typically less accurate with the expected RMS of better than 20 cm. In this study we used the satellite altimetry data with 10-day resolution (from January 2003 to August 2010) to estimate the water height variations in the Poyang Lake Basin.

2.4. *GLDAS model*

The GLDAS model is a joint project of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Prediction (NCEP). The input variables of this model include precipitation, solar radiation, surface pressure, humidity and surface wind horizontal speed data from NCEP. The variables from GLDAS include soil temperature, soil moisture, snowfall rate, runoff, etc. Currently, GLDAS drives four land surface models: Mosaic, the Community Land Model (CLM), the Variable Infiltration Capacity (VIC) with $1^\circ \times 1^\circ$ spatial resolution, and the Noah with both $1^\circ \times 1^\circ$ and $0.25^\circ \times 0.25^\circ$ spatial resolution, covering latitude 60°S–90°N, longitude 180°W–180°E in the form of grids. River basin TWS is total water mass variation as the integration of precipitation, evapotranspiration and runoff, namely

$$\mathrm{dTWS/dt} = P - ET - R \tag{2}$$

where P is the precipitation, ET is the evapotranspiration and R is the runoff. Neglecting R, the derivative of TWS is related to (P–ET). We adopted the values of the soil moisture and snowfall from the GLDAS VIC and Noah models to estimate the TWS variations in the Poyang Lake Basin. We then converted the gridded values of the TWS variations into the spherical harmonic coefficients with the same spectral resolution as used for the GRACE observations and used the filtering according to Swenson and Wahr [20] with subsequent application of the Gaussian smoothing function. The resulting spherical harmonic coefficients are then converted back to the grid values of the TWS variations.

2.5. TRMM data

The TRMM was launched in November 1997 by NASA and the National Space Development Agency (NASDA) of Japan. The TRMM mission carries 5 instruments, consisting of a 3-sensor rainfall suite (PR, TMI, and VIRS) and 2 related instruments (LIS and CERES). The TMI and PR are the main instruments used for monitoring the precipitation. Until now, the TRMM data provide valuable information for better understanding of tropical cyclone structure and evolution, climate and weather change, lightning-storm relationships, convective system properties, and human impacts on rainfall. These data also contribute to monitor flood and drought and weather forecast. In our study, we used the 3B31 data to estimate the rainfall variations over the Poyang Lake Basin. These data are provided at a 0.5° × 0.5° spatial resolution with the coverage between 40°S and 40°N in latitudes and 180°W–180°E in longitudes.

3. Results and discussions

3.1. Seasonal TWS variations

The TWS variations in the Poyang Lake Basin are estimated from the GRACE Level-2 RL05 solution for a period from January 2003 to March 2014. This dataset has lack of data in June 2003, January 2011, June and November 2012, March, August 2013, September 2013 and February 2014, which are interpolated. Since the TWS variations have significant seasonal signals, we used the following function, including the annual and semi-annual variations, linear trend and half acceleration terms, to fit the TWS [5]:

$$\mathrm{TWS}(t) = a + bt + ct^2 + \sum_{k=1}^{2} d_k \cos(\omega_k t - \varphi_k) + \epsilon(t) \tag{3}$$

where a is the constant, b is the trend, c is the half acceleration, d_k is the annual amplitude, φ_k and ω_k are phase and frequency, respectively, and $\epsilon(t)$ is the un-modeled residual term. The subscript $k = 1$ is for the annual variation and $k = 2$ is for the semi-annual variation in equation (3). Fig. 2 shows annual

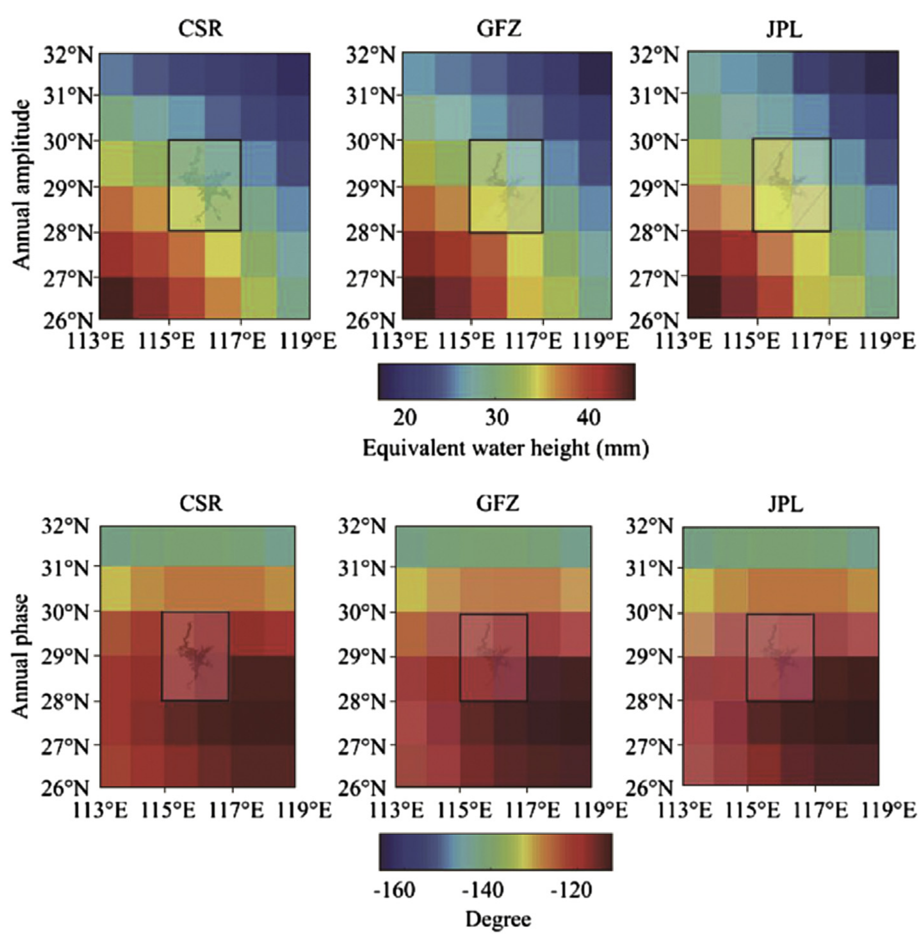

Fig. 2 – Annual amplitudes (top panel) and phases (bottom panel) of the TWS variations in the Poyang Lake Basin from GRACE CSR, GFZ and JPL solutions.

amplitude and phase of TWS in the Poyang Lake Basin from GRACE provided by CSR, GFZ, and JPL centers. The three solutions show similar estimates at seasonal timescales with negligible differences. The RMS residuals are 12.8 mm, 13.6 mm and 14.9 mm from CSR, GFZ and JPL solutions.

For example, from CSR solutions, the annual amplitude is 28.1 mm, the annual phase is −120.3°, while the semi-annual amplitude and phase are 7.9 mm and 29.2°, respectively. The TWS in the Poyang Lake Basin reaches maxima in August and minima in February.

The monthly averages of TWS over the period from 2003 to 2014 in the Poyang Lake Basin are shown in Fig. 3. These changes indicate the presence of enhanced seasonal pattern with the positive TWS values from June until October and the monthly maxima of 33.8 mm in terms of EWH in August. The TWS is negative from November to May of the next year with the minima of −22.6 mm in terms of EWH in February.

The TWS of the Poyang Lake Basin increases gradually with receiving annual peak inflow from its tributaries and the rising rainfall in the Poyang Lake Basin during March to June. From July to September, it recharges to the lake decreases affected by the northwestward monsoon front and the reducing rainfall in the Poyang Lake Basin. Meanwhile, the Yangtze River receives its annual peak precipitation and its outflow increases [21]. Thus, the water level of the Poyang Lake Basin rises rapidly and generally reaches the maxima in August, which agree with the results in Fig. 3 [22,23]. Following the decrease in rainfall in the Poyang Lake Basin and the reducing recharge from the five major tributaries, the TWS begins to decline and falls to the minimum in February [24]. On the other hand, the Three Gorges Reservoir reduces the flow into the Yangtze River, and the water level of Poyang Lake Basin rises relatively, which increases the water discharge from the Poyang Lake into the Yangtze River [25] and contributes to the reduction in TWS during that period.

TWS is a combined contribution of soil moisture in all layers, accumulated snow, plant canopy surface water and groundwater, but GLDAS does not contain groundwater variations. Fig. 4 shows the seasonal variations of TWS estimated from the VIC and Noah models over a period

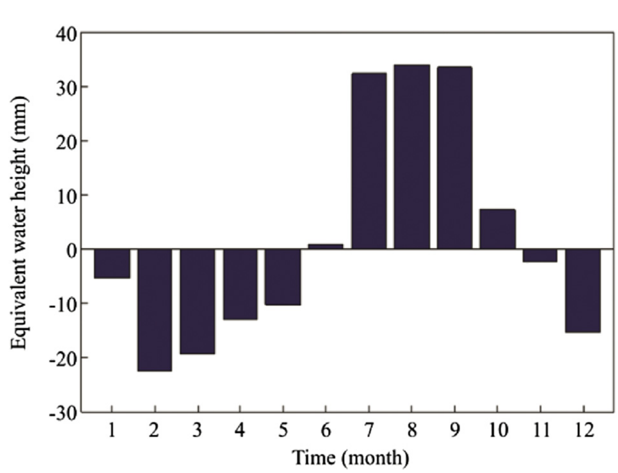

Fig. 3 – Monthly changes of TWS in the Poyang Lake Basin.

from January 2003 to April 2014. The comparison reveals some minor differences between these two models mainly determined by the soil layered structure. The soil structure of the Noah model is divided into 4 layers, while the VIC model consists of 3 layers, which are supported by the study of Fan et al. [26]. Moreover, the seasonal variations of TWS estimated from GLDAS show a good agreement with the results from GRACE, which are a slightly smaller in the annual amplitude, annual phase, semi-annual amplitude and semi-annual phase from GLDAS. The annual phase from GLDAS model (the average of Noah and VIC) is −64.9°. From equation (3), we can know that the TWS in the Poyang Lake Basin reaches maxima about in August and in June from GRACE and GLDAS, respectively, which indicates a phase lag of about two months between GRACE and GLDAS model.

The secular trends in the TWS variations estimated from GRACE and GLDAS between January 2003 and April 2014 are shown in Fig. 5. The GRACE and GLDAS results have a good agreement in their secular trend. The mean secular trend of the TWS variations in the Poyang Lake Basin is 1.7 mm/a from GRACE, 2.0 mm/a from VIC, and 1.9 mm/a from GLDAS Noah.

In order to compare the TWS variations from GRACE, GLDAS and satellite altimetry, we further plotted the TWS variations by the means of their volumes. The lake water volume of each month was computed by multiplying the equivalent water height obtained from GRACE and GLDAS by the basin area (162.2×10^3 km^2). Similarly, the water level from satellite altimetry is multiplied by the lake area (3283 km^2). The annual signal was removed and data were smoothed by applying the one-year window. As we can see in Fig. 6, the water volumes variations from GRACE, GLDAS and satellite altimetry are similar. The correlation between the GRACE and GLDAS is 0.51 and the corresponding correlation between the GRACE and satellite altimetry solutions is 0.63. The time series of GRACE observations exhibits significant inter-annual and seasonal changes in the water volume over the Poyang Lake Basin ranging from −9 to 12 km^3. The distinct decline of water volumes during 2006 and 2011 inferred from GRACE is consistent with the major drought events [27] in this studied area during these two years. In contrast, the increase of water volumes in 2010 coincides with the flood disaster as reported by China News Service in that year.

The studied area of the Poyang Lake Basin is characterized by rainy season from April to June and dry season from October to March. The precipitation has great changes with the season, combined with the variation of the inflow of the five major tributaries and the flood period of the Yangtze River, which give rise to the seasonal variations of TWS. It begins to rise gradually from March, and increases rapidly from July to September and reaches the maxima in August, and then starts to decrease and falls to the minimum value in February, which is consistent with the seasonal variations in Fig. 3. In addition, the trends of TWS in the Poyang Lake Basin are increasing at 0.0141 km^3/a and 0.0328 km^3/a from GRACE and GLDAS, respectively (from January 2003 to April 2014), while the trend is 0.0238 km^3/a from satellite altimetry data (between January 2003 and August 2010).

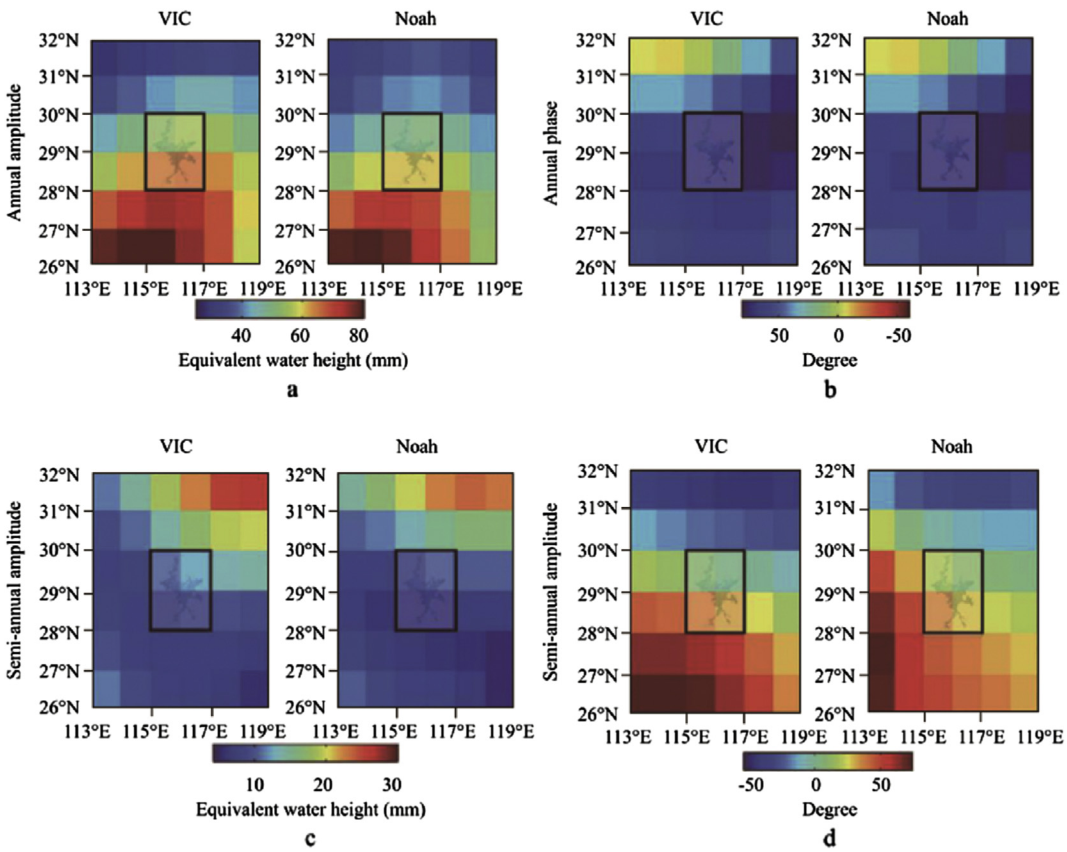

Fig. 4 – Seasonal variations of TWS in the Poyang Lake Basin from GLDAS.

3.2. *Impact of soil moisture on TWS variations*

We further investigated the contribution of soil moisture, accumulated snow, plant canopy surface water and groundwater to TWS over the studied area. The groundwater storage can be obtained after subtracting the GLDAS land surface total water storage from the TWS determined by GRACE. The correlation coefficient of soil moisture and GRACE TWS is 0.53, and the correlation between groundwater and TWS is 0.41. Moreover, the accumulated snow and plant canopy surface water ranges from −1 to 1 mm (in terms of EWH), which can be ignored. As seen in Fig. 7, the soil moisture content ranges from −84 to 78 mm (in terms of EWH). These values are slightly larger than the TWS variations. Both soil moisture content and TWS exhibit a typical seasonal pattern. Moreover, their correlation coefficient is 0.53. Over the investigated period, the soil moisture content reached maxima of 78 mm (in terms of EWH) in July 2006 and minima of −84 mm (in terms of EWH) in December 2009. The annual pattern of the soil moisture content is characterized by an increasing trend from January to June with the maxima mainly in June. From July to December, the

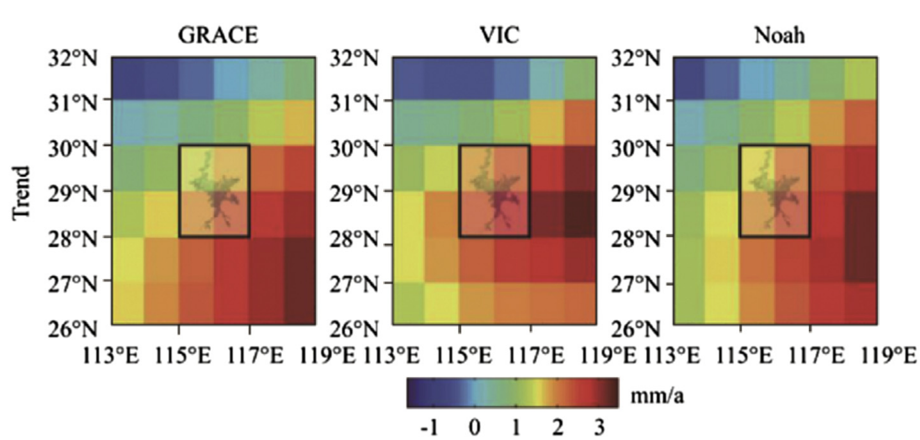

Fig. 5 – Trend of the TWS variations from GRACE and GLDAS.

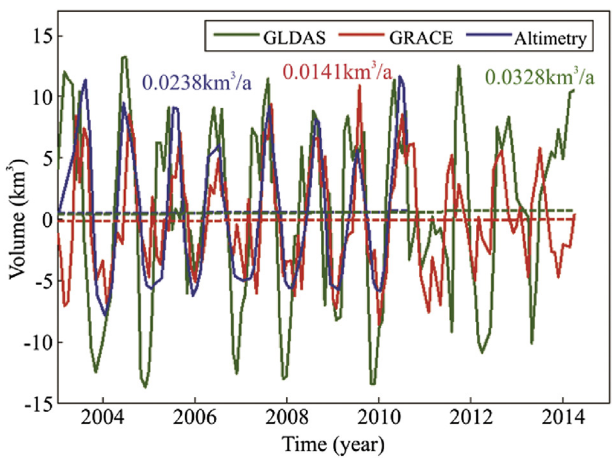

Fig. 6 – Comparison of water volumes variations from GRACE, GLDAS and satellite altimetry.

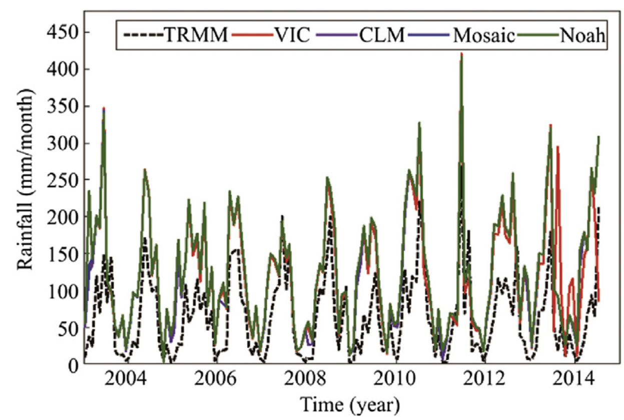

Fig. 8 – Rainfalls from TRMM and GLDAS models.

soil moisture content typically declines with minima in December. Similarly, the TWS increases from March and reaches maxima in August and then declines and reaches minima in February. Compared with the change cycle of TWS from GRACE, the soil moisture content precedes TWS by about 2 months. Therefore, the TWS is governed mainly by soil moisture content.

3.3. *Impact of rainfall on TWS*

We estimated the rainfall from TRMM and compared the result with the four GLDAS models (CLM, Mosaic, Noah, and VIC). The comparison is shown in Fig. 8. The rainfalls estimated from the GLDAS models are almost the same while have some differences with respect to the TRMM solution. The GLDAS rainfall models have a negative bias with respective to the TRMM solution, namely −37.5 mm/month for VIC model, −38.6 mm/month for Mosaic model, −38.7 mm/month for Noah model and −36.6 mm/month for CLM model.

The rainfall time series from TRMM and TWS from the GRACE data are shown in Fig. 9. The rainfall ranges from −75 to 213 mm (in terms of EWH), while the TWS ranges from −58 to 73 mm (in terms of EWH). Moreover, the rainfall reaches the maxima of 213 mm (in terms of EWH) in July 2011 and the minimum of −75 mm (in terms of EWH) occurs in December 2005. The precipitation and TWS have obvious seasonal variations and their correlation is 0.56. Moreover, both trends have no obvious irregularities between 2003 and 2005. The decreasing trend of the TWS in 2006 was consistent with the constantly low rainfall from October 2005 to May 2006. The TWS and rainfall slightly increased during the period from 2007 to 2009, while the TWS increased in 2010. This was consistent with the increased rainfall in 2010. Moreover, the results show no obvious changes in the TWS and precipitation between 2012 and 2014. The precipitation is mainly concentrated during the period between April and June, while the TWS also generally increases during this period. The precipitation is relatively low from December to March, while during this period TWS also decreases to its minima. Moreover, the rainfall precedes the TWS by about 2 months. The rainfall increased significantly from July to September in 2011. In contrast, the TWS decreased during those months. From these findings we could conclude that the TWS in the Poyang Lake Basin appears to be dominated primarily by precipitation but also modulated by the flood

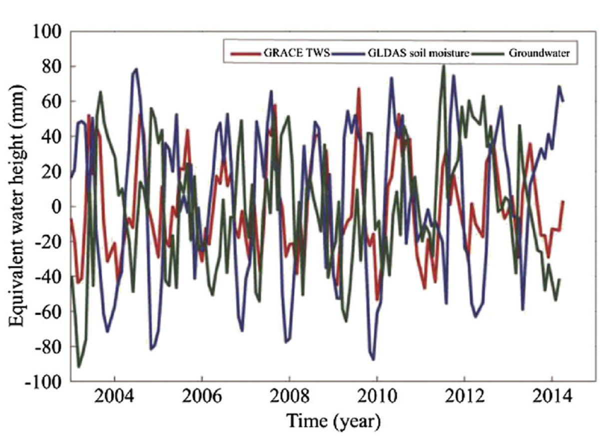

Fig. 7 – Comparison of the soil moisture content variations from GLDAS (the average of Noah and VIC), TWS variations from GRACE and groundwater.

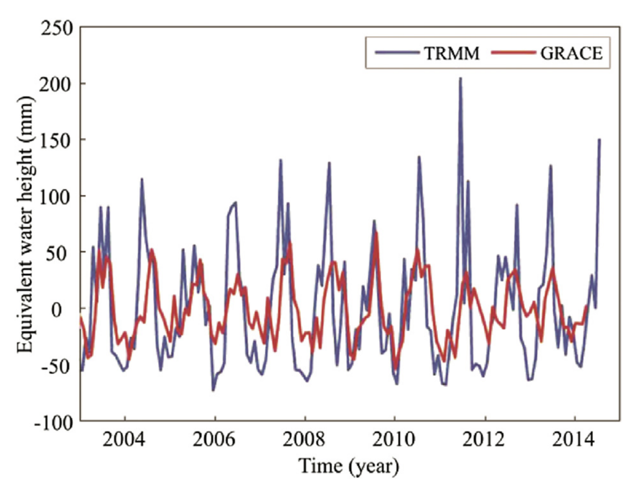

Fig. 9 – Comparison of rainfall variations from TRMM and the TWS variations from GRACE.

season of Yangtze River and the lake and river exchange water. During non-summer months, most of the TWS variations are driven by the local precipitation, while during summer months (from July to September) when the Yangtze River receives its annual peak precipitation and outflows from the Yangtze River to the lake is increased, the influence of precipitation became less significant.

4. Summary and conclusions

The TWS variations are investigated from the GRACE data during January 2003–April 2014 using the 500 km half-width Gaussian filter and the correlated-error filter. The GRACE TWS solution is compared with the results from GLDAS global hydrological models and satellite altimetry. The results show that the TWS variations have strong seasonal behaviors, and reach the maxima and minima in August and February, respectively. Generally speaking, it has a general agreement for GRACE, GLDAS and altimetry with correlation coefficients of 0.51 between GRACE and GLDAS and 0.63 between GRACE and satellite altimetry. Moreover, the trends of TWS in the Poyang Lake Basin are increasing at 0.0141 km^3/a, 0.0328 km^3/a and 0.0238 km^3/a from GRACE, GLDAS and satellite altimetry over the studied period, respectively. The correlation coefficient of soil moisture and GRACE TWS is 0.53, and the correlation of groundwater and TWS is 0.41, so the TWS is governed mainly by soil moisture content. Furthermore, we also find that the TWS appears to be dominated primarily by precipitation but also modulated by the flood season of Yangtze River and the lake and river exchange water.

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